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Response of Fly Ash Based Quarry Dust Cement Mortar to Magnesium Sulphate Attack

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ABSTRACT

Concrete is a ubiquitous construction material used globally to build bridges, homes, hospitals, schools and sewage systems. Concrete used in sewage systems is exposed to an aggressive environment, like elevated temperature and humid conditions, in addition to aggressive sulphate. The combined effect of these conditions results in the premature deterioration of structures. This study was investigated the effect of replacing cement by fly ash (FA) in cement mortar by different ratios and a quarry dust as sand. The reference mortar mix grade was (35 MPa) and the other mixes were with various percentages of FA (5%, 10%, 15%, 20%, 25%, 30%, and 35%) by weight of cement. This study evaluated the effect upon the compressive strength, splitting tensile strength, fracture strength, and modulus of elasticity of mortar containing FA exposed to the magnesium sulphate ($MgSO_4$) with concentration 30000 mg/l. Mixes were created using varying ratios of FA to identify the optimal concentration; these were compared against normal concrete. At replacement ratios of 20% at all ages, optimum compressive strength, splitting strength, fracture strength, and elastic modulus were obtained. Conversely, mixes with replacement ratios greater than 20% produced less strength than the control mix (without FA). The FA mortar's strength remained higher than that of regular mortar exposed to the same conditions of magnesium sulphate after 28 days, despite a reduction in compressive strength. As result, the replacing some of the cement in the concrete mix, particularly in the ratio of 20%, with FA, the concrete can be formed that is more resistant and more capable to withstand $MgSO_3$ attack.

1. INTRODUCTION

Portland cements containing mineral additives like FA and slag are increasingly often utilized in concrete construction. There is a considerable body of scientific evidence showing judicious integration of such pozzolanic/cementitious elements in concrete can improve its qualities in the fresh and hardened phases, particularly its durability [1]. Concrete is increasingly being utilized in civil engineering structures, such as substructures, infrastructure, and industrial floors that are frequently exposed to harsh environmental conditions, because of the advantages it offers. One of the main issues impacting concrete constructions is considered to be external sulphates, extremely soluble salts. The effects of sulfate attack often involve concrete volume change, cracking, and subsequent deterioration [2-4]. The quickest, most severe attacks on concrete are caused by magnesium sulphate ($MgSO_3$) [5, 6]. Magnesium sulfate is harsher than sodium sulfate. They generally come from soil, groundwater, seawater, or industrial wastewater, and their spectrum of media is broad [7]. The ions of the magnesium sulphate undergo a twofold reaction with the aluminate (or portlandite) to produce gypsum and ettringite. The ions Mg^{2+} may interact with OH- to generate brucite $Mg(OH)_2$, or they may promote a partial substitution of magnesium for calcium in calcium silicate hydrate (C-S-H). Due to the lack of binder qualities of the resulting magnesium silicate hydrate (M-S-H), the hydrated paste becomes floppy and coherent [8, 9]. Magnesium sulphate degradation is a well-known occurrence in normal concrete, and its effects have been the subject of numerous investigations [10-12]. The concentration of sulfate ions in the solution has a significant effect on the rate of expansion and damage that occur in concrete specimens; the larger the concentration, more intense the expansion. When using magnesium sulfate solution concentrations of 6250, 12500, and 25000 mg/L, the expansion rate of the mortar models increased by 0.02, 0.05, and 0.9%, respectively, indicating that some of the characteristics of the concrete were lost as the concentration of the solution increased [13]. It has been demonstrated that the concentration of SO_4^{-2} in magnesium sulphate solution impacts the sulphate attack mechanism [14]. When sulfate ions were present in amounts greater than 10,000 mg/l, a harsh environment started to develop on the concrete [15].

When additional cementitious materials such pozzolans and slags were added to Portland cement systems, the amount of portlandite in the mixture is reduced, and the pore structure is refined. As a result, the concrete has less permeability and is more resistant to sulfate attacks [16, 17]. Pozzolanic materials, such as FA and silica fume, have outstanding mechanical properties even after short aging times; however, due to the variability of their source materials, which generally come from industrial waste or byproducts, comprehensive research is needed to determine how long they can last in various environments [18-21].

In concrete, the purpose of the fine aggregate is to help the mixture become workable and uniform. The most typical source of fine aggregate is the deposits found in and beside rivers. Natural river sand is becoming extremely costly and difficult to survive on. We must thus consider alternate materials. Quarry dust may be used in full or in part in place of river sand. When quarry dust is used in place of sand, either partially or completely, together with or without concrete admixtures, a relatively good strength is obtained. With the replacement of sand, the w/c ratio and slump value increased. Because there were less voids in the mortar composed of quarry dust compared to sand, the compressive strength was higher [22-27].

This study investigates the effect upon compressive strength, splitting strength, fracture strength, and modulus of elasticity, of replacing cement with FA. Concrete grade (C 35) with various percentages of FA (0%, 5%, 10%, 15%, 20%, 25%, 30%, and 35%) were investigated and compared after an exposure-period of twelve weeks, curing in tap water and a sulphate solution. Additionally, the optimal FA replacement ratio was determined. Concrete specimens were exposed to solution of $MgSO_4$ with concentration 30000 mg/l for a total duration of twelve weeks. This concentration value was selected to assess the strength loss of concrete exposed to a harsher environment than that previously studied as well as the possibility of reducing this decrease by substituting cement with materials that have properties resistant to this type of harsh environment. To evaluate compressive strength, splitting strength, fracture strength, and elastic modulus concrete specimens were constructed as standard cubes (50×50×50 mm), standard cylindrical (100×300), standard prism (50×50×100mm), and cylindrical (150×300), respectively. Three specimens of each proportion of FA replacement were tested for 28, 60, and 90 days to both curing conditions.

2. EXPERIMENTAL PROGRAMME

2.1 Materials

2.1.1 Cement

The cement used in this investigation was Portland cement type I, manufactured and supplied by Kubyisa cement factory in the Iraq. Tests were carried out on the cement to determine its physical properties according to Iraqi standards (IQS: 5-1985) [28]. The properties of the Portland cement are illustrated in Table 1.

Table 1. Properties of Portland cement type I

	Property		Result
Physical properties	Fineness (m^2/ kg)		250
	Initial setting time (hr:min)		0:45
	Final setting time (hr:min)		9:30
	Compressive strength (Kg/mm^2)	3 days	16
		7 days	23
Chemical properties	SiO_2 (%)		-
	Fe_2O_3 (%)		-
	AL_2O_3 (%)		-
	CaO (%)		-
	MgO (%)		5
	CO_3 (%)		2.5
	Loss on Ignition (L.O.I)		4
	Insoluble residue (I.R)		1.5
	Lime Saturation Factor (L.S.F)		1.02-0.66

2.1.2 Quarry dust

Quarry dust: Material produced incidentally during the manufacture of stone for construction works. it was gathered from neighboring quarries and was an alternative material of natural sand. Sieve analysis within zoneII with fine particles less than 0.075 of 12-15%. Table 2 is a summary of the characteristics of quarry dust.

Table 2. Sieve analysis and properties of quarry dust

Properties	
Specific gravity	2.54
Fineness modulus	2.41
Density g/cc	1.8
Void ratio	0.41
Absorpation	1.4

2.1.3 Pozilanic material FA

Condensed FA has been classified as a pozzolan by the American Society for Testing and Materials (ASTM) [29]. The FA class F was used in this study with chemical components listed in Table 3.

Table 3. Components of Fly Ash

Component	Content
SiO_2	58.24
Al_2O_3	20.23
Fe_2O_3	5.33
TiO_2	0.45
Cao	7.62
MgO	2.01
Na_2O	0.52
K_2O	1.51
SO_3	2.21
P_2O_5	0.00
LIO	1.69

2.1.4 Super-plastizer

When cement and water are combined, the cement particles always flocculate and aggregate, and the electrostatic forces created by the electric charge on the particle surface cause the homogeneity of the concrete to deteriorate. With the addition of superplasticizers between the solid concrete particles, water-reducing or workability agents like plasticizers and superplasticizers become more uniform and viscous. The admixture with the qualities listed in Table 4 was a locally accessible admixture utilized as a superplasticizer.

Table 4. Properties of super plasticizer used

Properties	value
PH value	10±1.0
Specific gravity	1.2 kg/I
Appearance	Liquid

2.1.5 Magnesium sulphate

Environments surrounding concrete may contain magnesium sulphate; therefore, $MgSO_3$ solutions with concentration 30000m/l were prepared to mimic the harsh environment of concrete structures. It is emphasised that the speed at which concrete structures degrade is determined by the concentration of the magnesium sulphuric, as well as the quantity of water that can penetrate the surface of the concrete. The solutions should be considered for concrete when exposed to sulphate environment.

2.2 Mix proportion of cement mortar

An experimental investigation was carried out to study the properties of normal cement mortar, by partially replacing cement with a certain per cent of FA. To achieve a cement mortar mixture with a strength of 35 MPa as a control mixture, which was proposed in this study, various trials mixes were made by changing the proportions of cement, fine aggregates, water, and superplastizer. Once the optimum trial mix was achieved by weight propotion 1:2.9, a total of seven mixes were made by replacing cement with varying amounts of FA 0% (control mix) 4%, 8%, 15% and 20% for all specimens. The water/binder ratio was kept constant at 0.45. The quantities of mixes components are presented in Table 5.

Table 5. Proportions of the components in the cement mortar mixes (grade 35 MPa)

Mix proportions	Cement %	FA %	Superplas-ticizer (L/m^3)	W/C ratio W/b ratio
Mix 0	100	0	50.6	0.45
Mix 1	95	5	48	0.45
Mix 2	90	10	45.5	0.45
Mix 3	85	15	43	0.45
Mix 4	80	20	40.48	0.45
Mix 5	75	25	37.93	0.45
Mix 6	70	30	35.42	0.45

2.3 Casting and curing

Standard cubes of specimens (50×50×50 mm) were used to determine their compressive strength, cylindrical specimens (100×200) for splitting tensile strength, prism specimens (50×50×100) for fracture strength, and (150×300) cylindrical specimens to evaluate elastic modulus. Before casting, the moulds were cleaned and oiled properly. The constituent materials were weighed accurately and were mixed by electrical drum mixers, transferred by small trolley. To evaluate the resistance of prepared specimens against $MgSO_3$ attack, they were exposed to $MgSO_3$ solution with a concentration of 30000 gm/l, and the control mortar specimens were submerged in water. At the end of each test time period, three cement mortar specimens of each mix were taken out of the solutions. To dry out the specimens, they were put in a humidity-controlled room for 24 hours, where the relative humidity was maintained at 50%. Each of the specimens was tested on 7, 14, 28, 56 and 90 days.

3. RESULTS AND DISCUSSION

3.1 Effect of FA on the resistance of cement mortar

3.1.1 Compressive strength

Figure 1 shows that the compressive strength of 5%, 10%, 15%, and 20%, FA-substituted cement exceeds that of normal cement mortar about 4%, 10%, 14%, and 19% respectively, during the early curing stage (7-14 days). The compressive strength at 28 days of age was greater than the normal cement mortar of same ratios above with small different. At age 90 days, the improvement in compressive strength for all specimens aforementioned was continued. However, when 25% and more of the mix was replaced with FA, compressive strength declined sharply (see Figure 1). The improved compressive strength at 28 days was achieved by replacing Portland cement type I with 20% of fly ash is 19%. In summary, FA cement exhibited higher values of compressive strength than cement for all types of concrete specimens at FA 20%. A possible explanation for the elevated compressive strength of 20%-substituted FA cement mortar specimens is that this proportion optimised a reaction between FA and calcium hydroxide, resulting in the generation of secondary calcium silicate hydrate. When the FA content of the mixture is greater than 20%, more silicate is accessible through the FA than is required by the calcium hydroxide produced during the hydration of the cement. As a result, the remaining inactive elements in the combination diminish the mixture's strength. In the case of a replacement rate of less than 20%, there may not be enough silicate in return from the fly ash, resulting in some calcium hydroxide that is excess. Additionally, the reactive silicate elements offer greater strength than the control mix, and this value increases with amount to reach the optimal level for replacement.

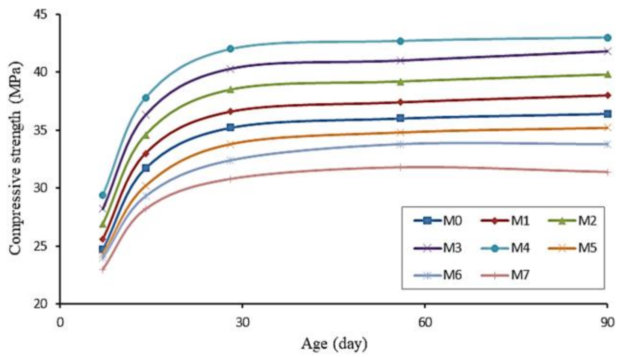


Figure 1. Effect of FA on compressive strength of concrete immersed in tap water

3.1.2 Splitting tensile

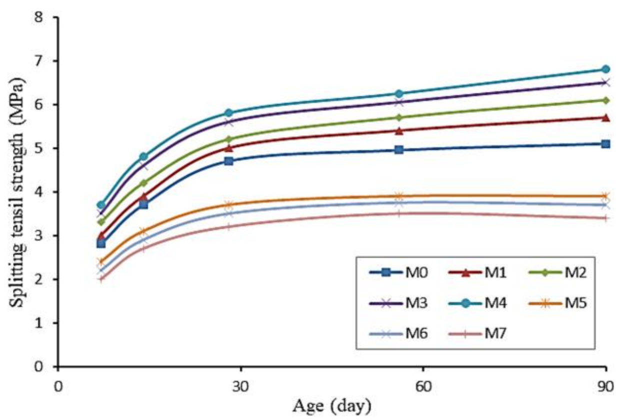


Figure 2. Effect of FA on splitting tensile strength of concrete immersed in tap water

Also known as the "Brazilian Test," a split tensile test. A cylindrical specimen is set horizontally between the loading surfaces of a compression testing device, and a load is applied until the cylinder fails along the vertical diameter. Average results for three models were taken for each replacement percentage. The results showed increasing in tensile strength for all cement mortar specimens more than the control mix without fly ash replacement except for the mixture in which the replacement percentage reached 30%, which gave a result less than the reference mixture, as shown in the Figure 2.

3.1.3 Fracture strength

Figure 3 depicts the resulting increase in fracture strength for cement mortars specimens up to 90 days age. The increase in fracture strengths were about 6%, 12%, 16%, and 20% for mortar specimens containing FA of 5%, 10%, 15%, and 20% respectively, when compared with control specimens (without FA) at age of 28 days. while at 90 days age, the increasing were 8%, 13%, 18%, and 22% rrespectively to the same proportions mentioned above compared with the control specimens. The fracture strength deteriorated with less severity than the control specimens at all ages, as was the case with the compressive strength for samples containing more than 20% FA.

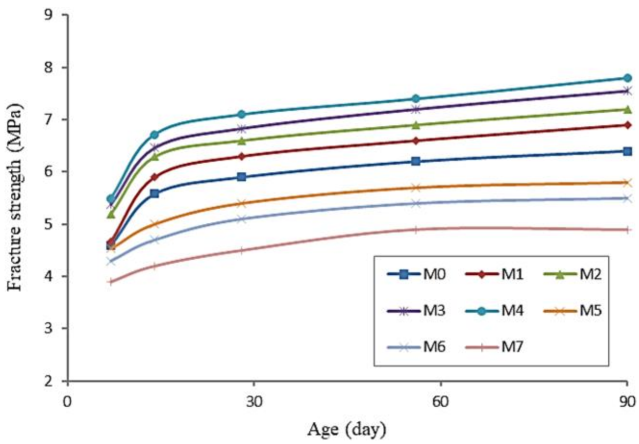


Figure 3. Effect of FA on fracture strength of concrete immersed in tap water

3.1.4 Elastic modulus

In this inquiry, the slope of the line drawn from the origin to any chosen point on the stress-strain curve is taken to be the modulus of elasticity, also known as secant modulus. A stress level corresponding to one-third of cube strength is used to compute the secant modulus. Concrete mixtures' modulus of elasticity are measured at the age of 28 days.

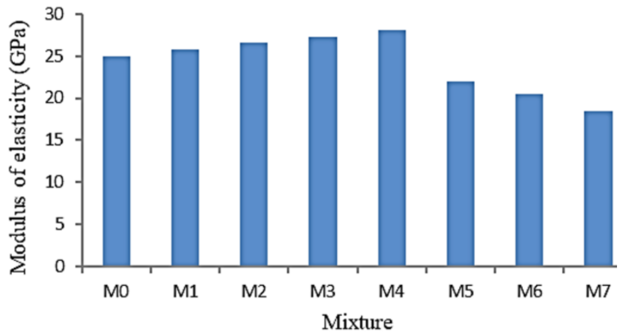


Figure 4. Elastic modulus of different FA replaced cement

From Figure 4, it can be seen that when 20% FA is used in place of cement, the elastic modulus achieves a maximum value that is 12.5% higher than the control specimen. However, when 5%, 10%, and 15% of FA is used in place of cement, the increment in elastic modulus are 3%, 6%, and 9%, higher, respectively This is due to the enhancement of cement past strength and good bond with fine aggregate of cement mortar [30]. While the mortar specimens with 25%, 30%, and 35% FA replaced cement resulted 12%, 18%, and 26% decrement respectively in elastic modulus. This is because a high replacement level of fly ash, which is unable to participate in the hydration process, has a packing effect [31].

3.2 Effect of magnesium sulphate attack

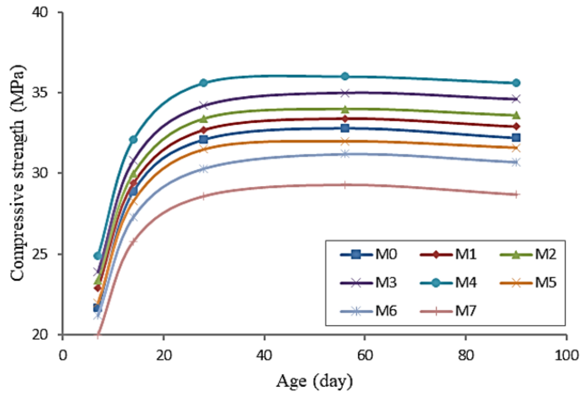


Figure 5. Effect of fly ash on compressive strength of cement mortar immersed in $MgSO_3$

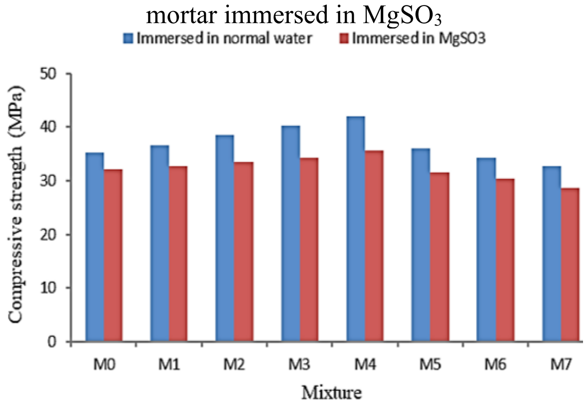


Figure 6. Compressive loss of specimens with 20% fly ash immersed in water or $MgSO_3$ at 28 days

3.2.1 Compressive strength

To measure the effect upon compressive strength after 90 days of exposure to aggressive sulphate, plain and fly ash-substituted mortar specimens were compared to comparable specimens exposed to plain (tap) water for the same duration. From time-to-time during the experiment, specimens were withdrawn from the sulphate solution, and subjected to visual inspections of the concrete surface and interim measurements taken. Visual inspection of these specimens revealed the cement matrix had different little lighter colour, which is attributed to expansion and dissolution. Figure 5 presents the effects that different percentages of concrete admixtures have upon the compressive strength of concrete at 7, 14, 28 and 90 days. The data indicate that at 28 days, concrete mixtures containing FA and submerged in water or sulphate, had better compressive strength than regular concrete exposed to comparable submersion conditions. Specimens exposed to the $MgSO_3$ environment had lower strength than those exposed to water. This is explained by the enhanced solubility of gypsum and ettringite in sulphate solutions than in water. The effect of increased solubility in $MgSO_3$ is that these materials slowly leach out of the mortar, gradually making the mortar more porous, which in turn reduces its compressive strength [32]. In contrast, specimens cured in water sustain greater compressive strength because $Ca(OH)_2$ is not soluble and thus, is retained in the concrete. Figure 6 depicts the change in the compressive strength of the concrete specimens with 20% FA after various durations of exposure to acid and water environments. It can be seen that the magnesium sulphate attack slightly increases after 28 days and all the mortar specimens for all grade mixtures have lower compressive strength at 90 days.

3.2.2 Splitting tensile strength

Figure 7 presents the effects that different percentages of cement mortar admixtures have upon the splitting tensil strength of concrete at 7, 14, 28 and 90 days. The data indicate that at 28 days, concrete mixtures containing fly ash and submerged in $MgSO_3$, had better tensil strength than regular mortar exposed to comparable submersion conditions. Specimens exposed to the $MgSO_3$ environment had lower strength than those exposed to water about 17.5% to control specimens, and 13.5%, 10.5%, 8.7%, and 7.4% for mixes containing FA ratios of 5%, 10%, 15%, and 20% at 28 days respectively, with slightly decreasing compared with control mix. Figure 8 shows the loss of tensil strength to optimal mix (20% FA) submerged in $MgSO_3$ and normal water at age 28 day.

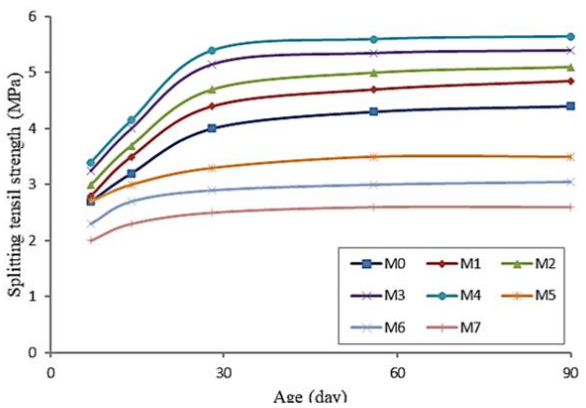


Figure 7. Effect of fly ash on splitting tensil of cement mortar immersed in $MgSO_3$

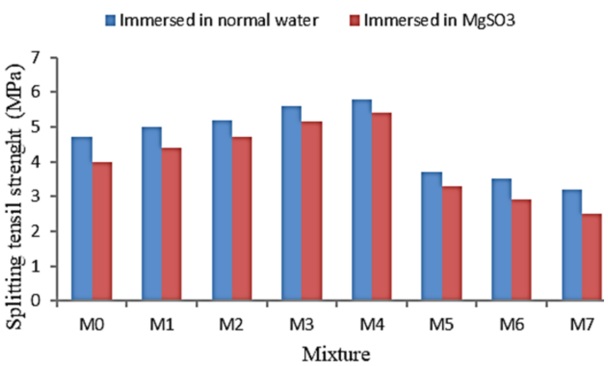
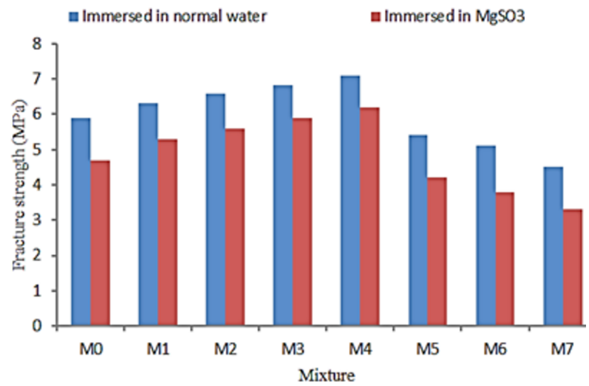


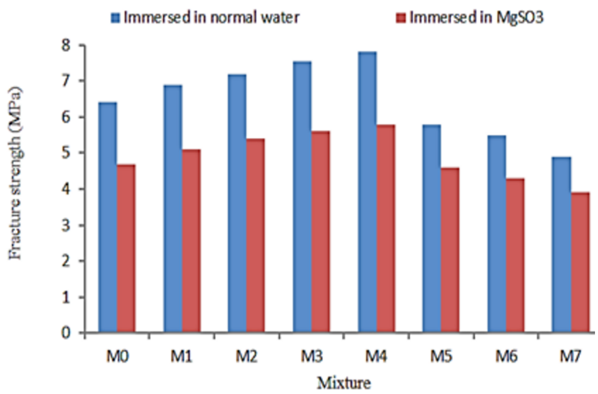
Figure 8. Splitting tensil loss of specimens with 20% fly ash immersed in water or $MgSO_3$ at 28 days

3.2.3 Fracture resistance

The fracture strength reduction for the mortar specimens immersed in sulphate compared with those immersed in normal water after 28 and 90 days is shown in Figures 9(a) and (b). When compared to specimens immersed in normal water at day 28, those containing 0%(control) 5%, 10%, 15%, and 20% of $MgSO_3$ had fracture strengths that were 25.5% (contral), 18.9%, 17.8%, 15.7%, and 14.5% lower. Whereas samples with more than 20% fly ash produced results that were inferior to those of control samples. At 90 days old, none of the specimens immersed in sulphate produced results that were superior to those of the specimens immersed in normal water. The reason is that the remedy has a significant impact on how quickly cracks develop [33].



(a) At 28 days



(b) At 90 days

Figure 9. Fracture strength of mixtures immersed in water and $MgSO_3$

3.2.4 Elastic modulus

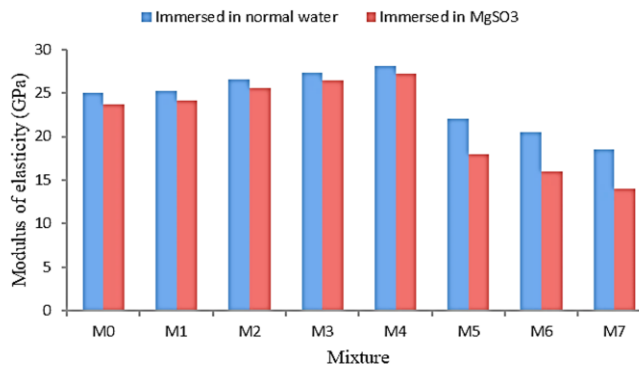


Figure 10. Percentage of elastic modulus lost by mortar specimens containing various amounts of FA, cured in water or $MgSO_3$ for 28 days

The elastic modulus values for mortar specimens submerged in water and $MgSO_3$ at 28 days are shown in Figure

10. The results revealed that as fly ash replacement rates for cement increased by up to 20%, the modulus of elasticity also increased. The modulus values in the specimens with fly ash ratios of 0% (control), 5%, 10%, 15%, and 20% submerged in $MgSO_3$ decreased by 5.5% (control), 4.5%, 3.9%, 3.4%, and 3.3%, respectively. In every instance of immersion, the elastic modulus values of the specimens containing more than 20% FA dropped.

4. CONCLUSION

The combination of FA with Portland cement was used with high-strength concrete grade to evaluate the degradation of the cover of concrete structures, due to aggressive solutions. Pozzolanic materials and industrial by-products, such as FA are used in concrete to improve its properties, mainly by making it denser. However, the performance of these materials under different environments is not well documented and discussed. Therefore, the aim of this study was to compare the resilience and strength of regular cement mortar and cement mortar containing various amounts of FA that had been exposed to a $MgSO_3$ environment. On the basis of the results obtained in this study the following conclusion can be drawn:

1. In terms of optimising the compressive strength of the cement mortar, FA provided maximal effect, when it comprised 20% of the mortar mix. FA concentrations of either side of this peak still provided greater compressive strength compared to plain mortar.
2. Despite a drop in compressive strength after 28 days, the FA mortar's strength remained better to that of normal mortar exposed to the same conditions of magnesium sulphate.
3. The cement mortar specimens in which FA replaced cement and immersed in $MgSO_3$ showed lesser losses in term of splitting tensile strength, fracture strength, and modulus of elasticity than the normal mortar specimens.
4. The external appearance of the normal concrete specimens was affected more clearly than the FA concrete up to age 90 days through the simple change in their color.
5. The concrete can be produced more durable and better able to withstand $MgSO_3$ attack by FA being replaced to some of the cement in concrete mix especially in ratio 20%.

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